NN-EXPLORE:
WIYN Stage 1 Science

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With Contributions from:
Lori Allen, Di Harmer, Knicole Colon, Joel Hartman, Verne Smith, Mark Giampapa, Nic Scott

NN-EXPLORE GO Program

NASA and NSF should support an aggressive program of ground-based high-precision radial velocity surveys of nearby stars in order to validate and characterize exoplanet candidates. Need candidates (K2 and TESS and other sources) and additional ground-based observations as well.

NN-EXPLORE will "conduct ground-based observations that advance exoplanet science, with particular emphasis on Kepler, K2, and (eventually) TESS follow-up observations and on observations that inform future NASA missions, such as the James Webb Space Telescope (JWST) and the Wide Field Infrared Survey Telescope – Astrophysics Focused Telescope Assets (WFIRST-AFTA) mission.

NN-EXPLORE GO Program

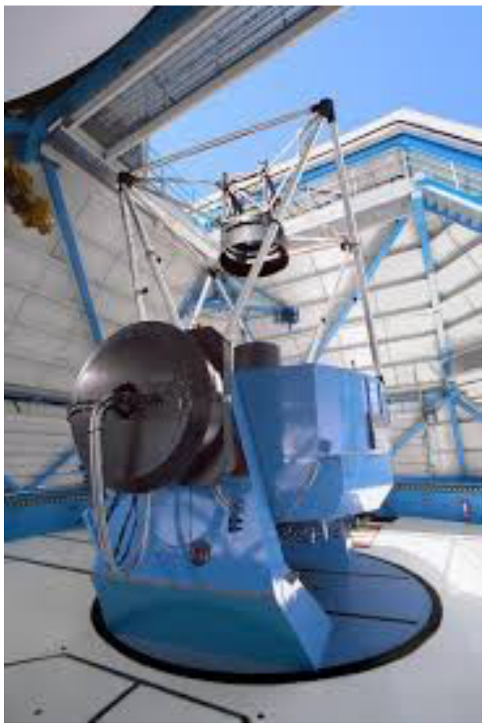
- **Stage 1 – Pre-commissioning (through Sep 2019)**

  Simultaneous with the instrument development, NASA will manage an exoplanet-targeted Guest Observer program with existing instrumentation using NOAO share of WIYN (40%; approximately 100 nights/year, ~50/semester).

- **Stage 2 Post-commissioning (Starting in Oct 2019)**

NN-EXPLORE GO Program

- GO program is already under way
  - Started in Semester 2015B (1 Aug 2015 – Jan 31 2016)
  - Semester 2016A (1 February 2016 – 30 July 2016)
  - Semester 2016B (1 Aug 2016 – 31 Jan 2017)
    - Proposals just selected.



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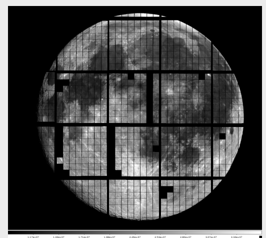
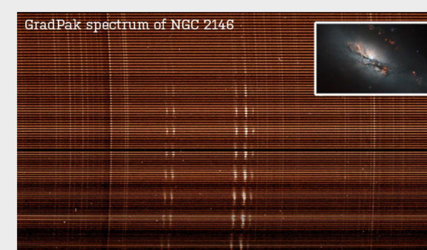
Imaging	Spectroscopy
One Degree Imager "ODI" 0.1" pixels; 40'x48' fov SDSS u', g', r', i', z' filters Science pipeline 	HYDRA ~100 fibers red or blue; ~1 deg fov Feeds bench spectrograph Data reduction cookbook
WIYN High Resolution Infrared Camera (WHIRC) 0.1" pixels; 3.3' x 3.3' fov J,H,K + 10 narrowband filters WIYN Tip-Tilt Module (WTTM) = fast guider Data reduction cookbook	IFU modules Visitor Instrument (Bershady) SparsePak, GradPak, HexPak Feeds bench spectrograph
Differential Speckle Survey Instrument (DSSI) Visitor Instrument (Howell/Horch) Simult. 2-band, diffraction-limited images V~14.5, 0.04" resolution (650nm), 2.8" fov Queue mode + science pipeline. WIYNSPKL coming Oct. 2016	Bench spectrograph R = 800 – 20,000 $\lambda\lambda$ = 300 – 1000 nm 

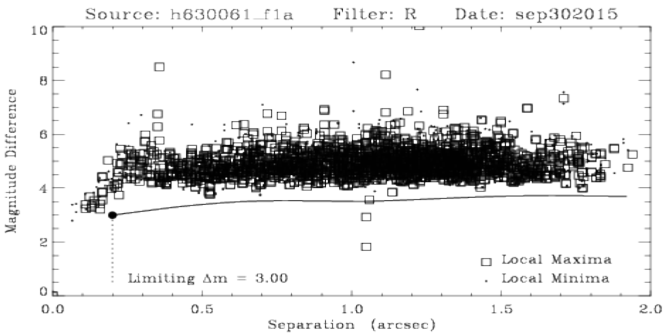
NASA/WIYN proposals

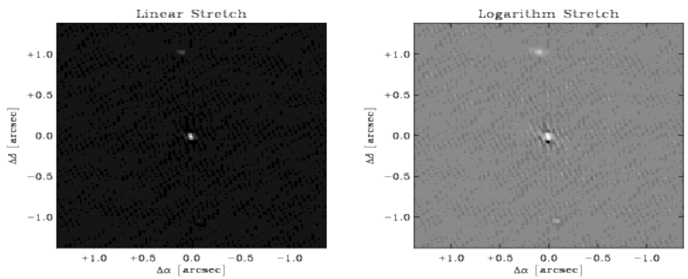
Instrument	2015B #prp/#nts	2016A #prp/#nts	2016B #prp/#nts
NASA-GO	**16/59**	**18/85**	**16/54**
HYDRA	8/37	9/46	7/28
DSSI	6/17	5/17	5/13
WHIRC	2/5	3/15	2/8
ODI	---	1/10	2/5
IFUs	---	---	---

Instrument Use

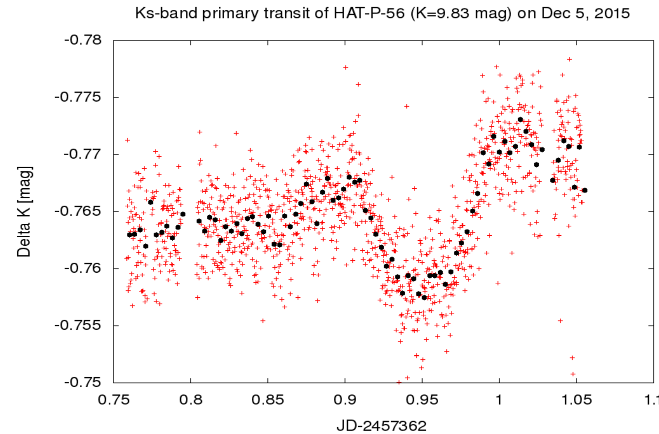
- Instruments:
  - ODI – multiple colors, transit light curves, comparison star(s)
  - HYDRA one to a few fibers, exoplanet host characterization, metallicity
  - WHIRC transit light curves
  - DSSI (queue mode) – host star multiplicity, (small) exoplanet validation, CFOP contributions
- Note: very little Exoplanet science done at WIYN prior to NN-EXPLORE program except DSSI; used since 2008 for Kepler FOP, now K2 ExoFOP

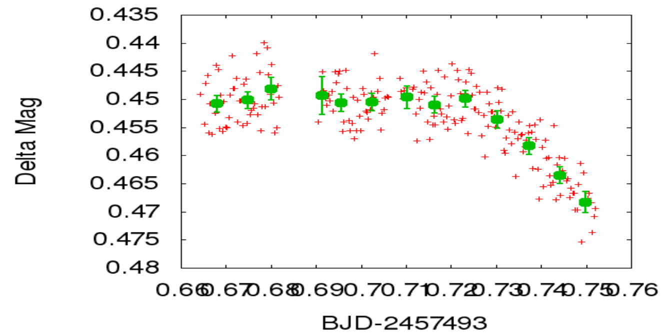
Follow-up of HATNet Exoplanet Candidates: Joel Hartman





DSSI detects (low-mass) stellar companions to transiting planet candidates from HAT. 79 HATNet targets have been observed, 9 confirmed planets





WHIRC observes primary or secondary transit events. Top: K-band transit for HAT-P-56b. Bottom: J-band ingress → EB; deeper transit in J than r-band.

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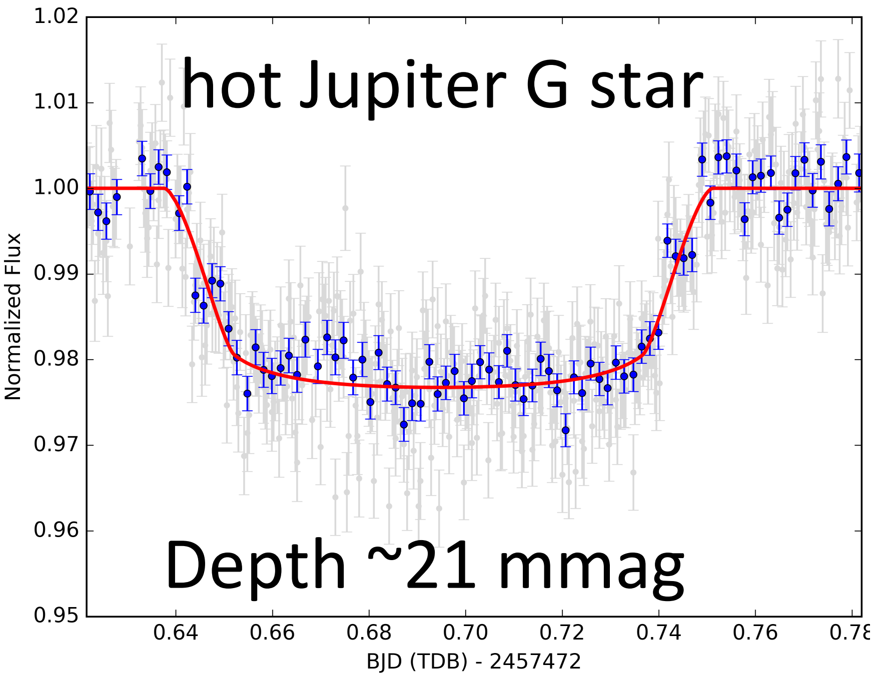
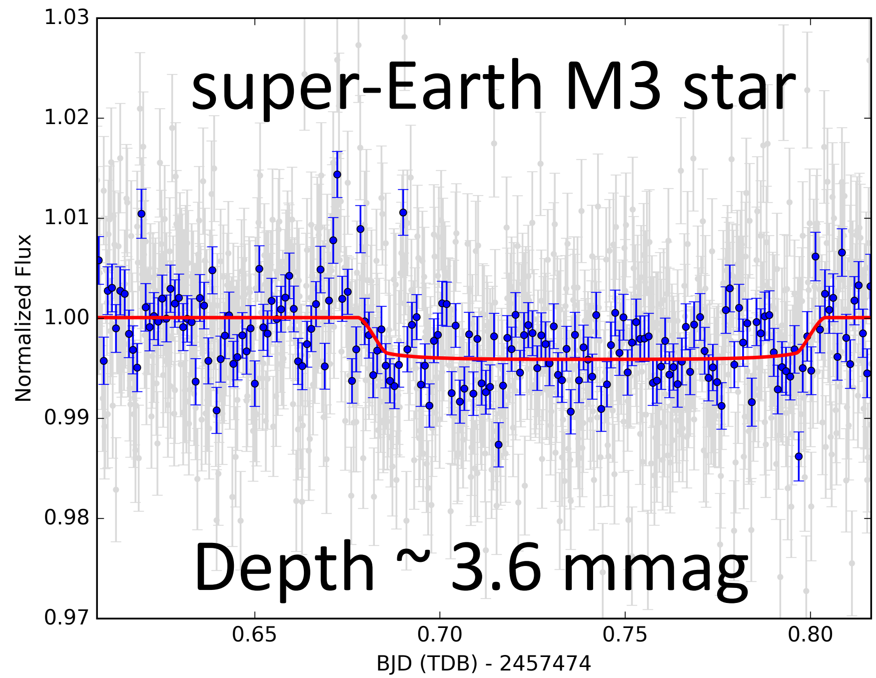
K2 NIR Transit Follow-Up @ WIYN

Knicole Colón

- Goal is to validate and characterize K2 exoplanets
- Observed 8 targets during 24-29 March 2016 run with Rp = 1.44-10.9 Re and Ks = 8.9-12.4





K2 and WIYN/Hydra Observations of Solar-type Stars in M67

Mark Giampapa

A. Önehag et al.: M67-1194, an unusually Sun-like solar twin in M67

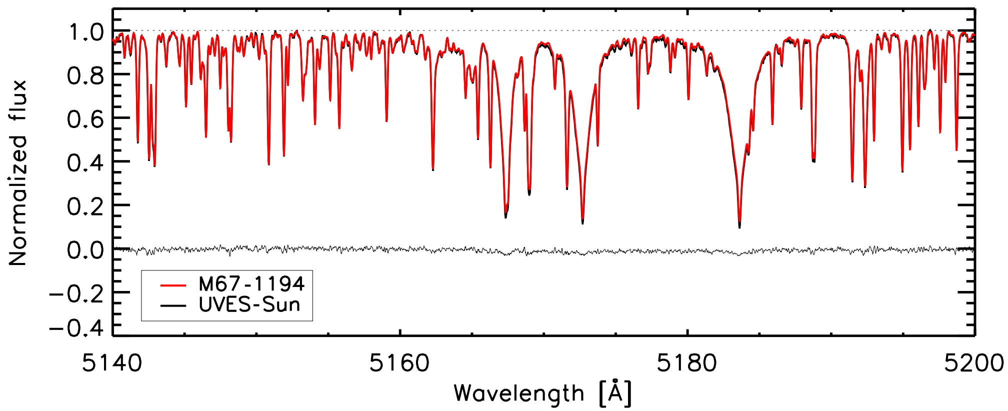
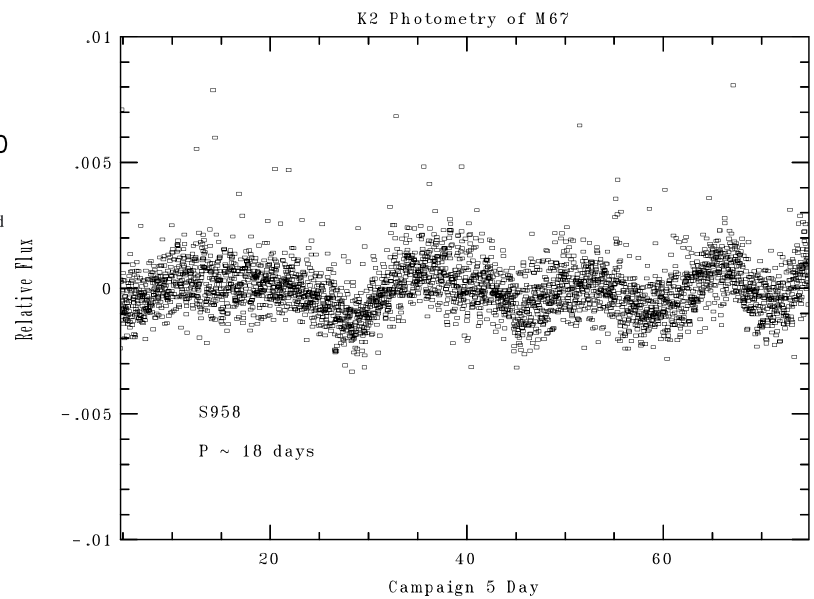


Fig. 2. Observations of the Mg *ıb* triplet region, for both M67-1194 (black) and the FLAMES-UVES Sun (red). A difference spectrum is plotted below.

Mg b triple region – red = host star,
black = UVES solar spectrum. Difference
Shown at bottom.

K2 light curve of same star



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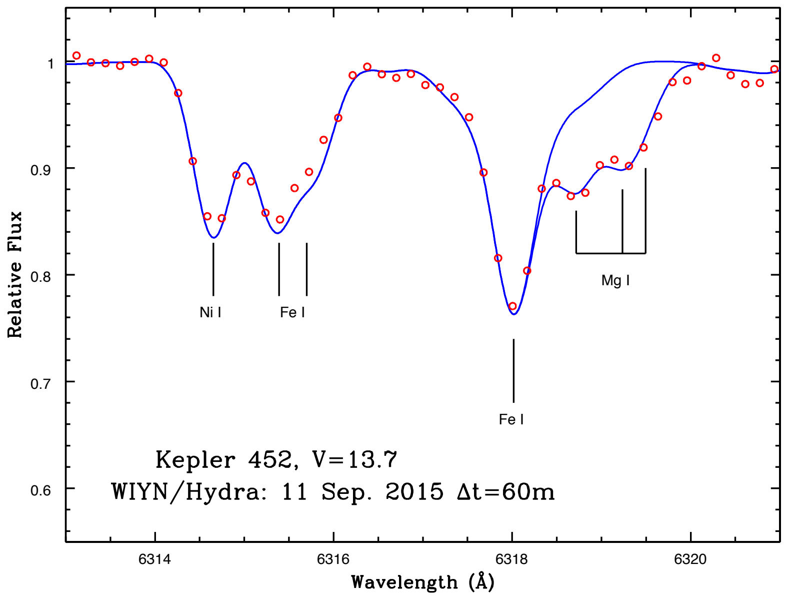
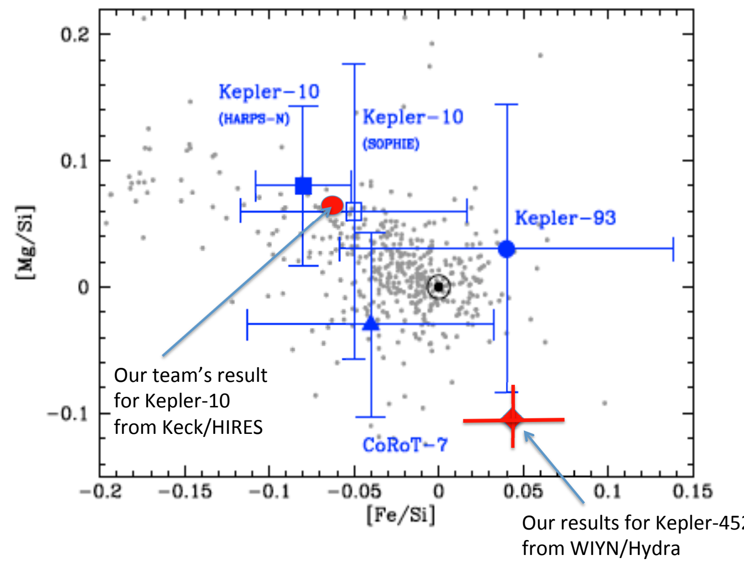
Accurate Stellar Characterization & Metallicity for Kepler and K2 Exoplanet Host Stars

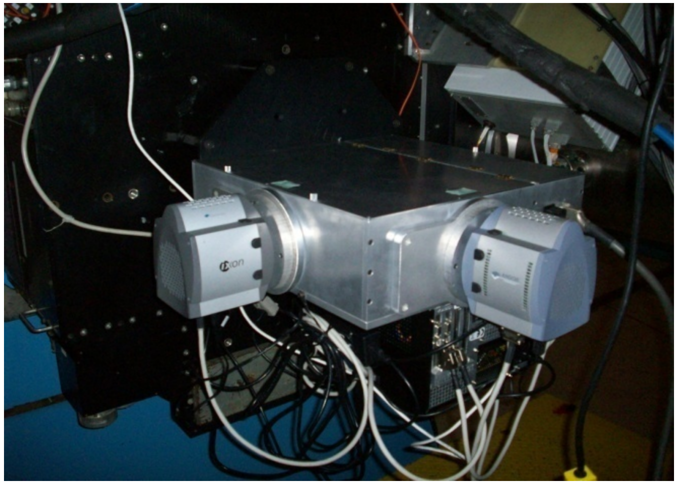
V. Smith, K. Cunha, C. Martinez, J. Teske, S. Howell, S. Schuler, L. Ghezzi



Results for Kepler 452: Spectra used to derive values for T_{eff}, log g, metallicity, plus detailed abundance distributions. WIYN/Hydra spectrum showing Mg I.



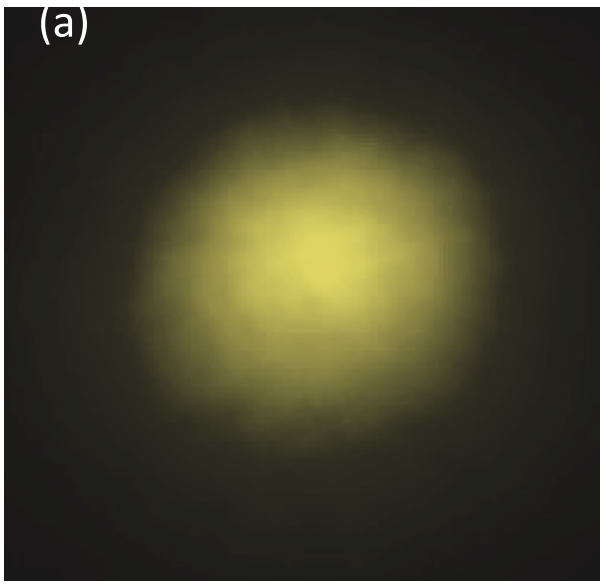
The ratio of [Mg/Si] plays a role in the structure of rocky planets.

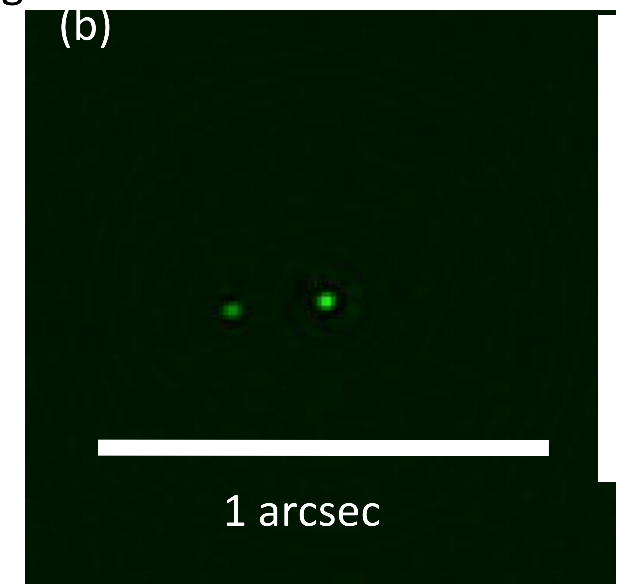


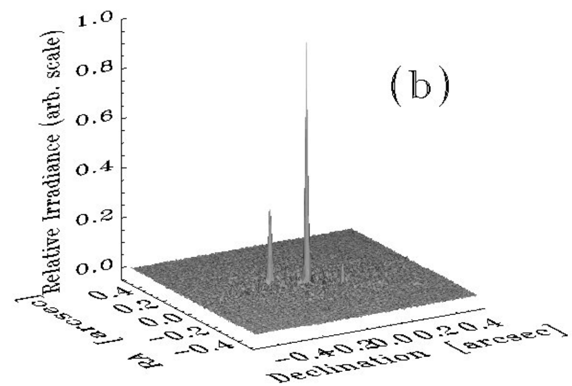
WIYN Speckle Imaging: Companion Detection & (Small) Exoplanet Validation

Panchromatic Integrated Image

Reconstructed Images – What WIYN + Speckle sees
562 nm







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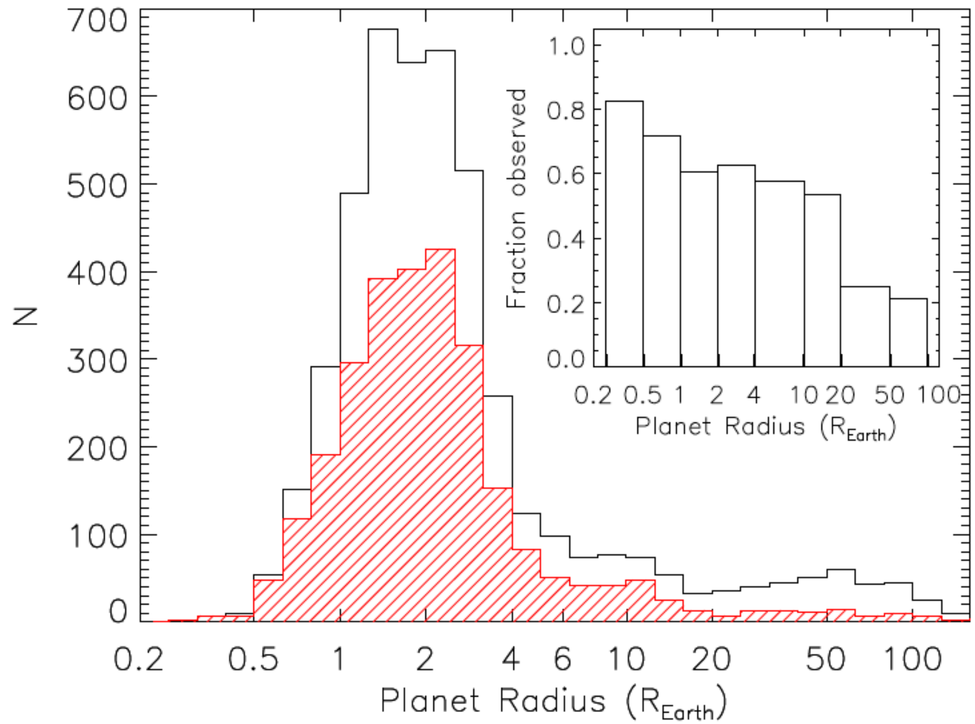
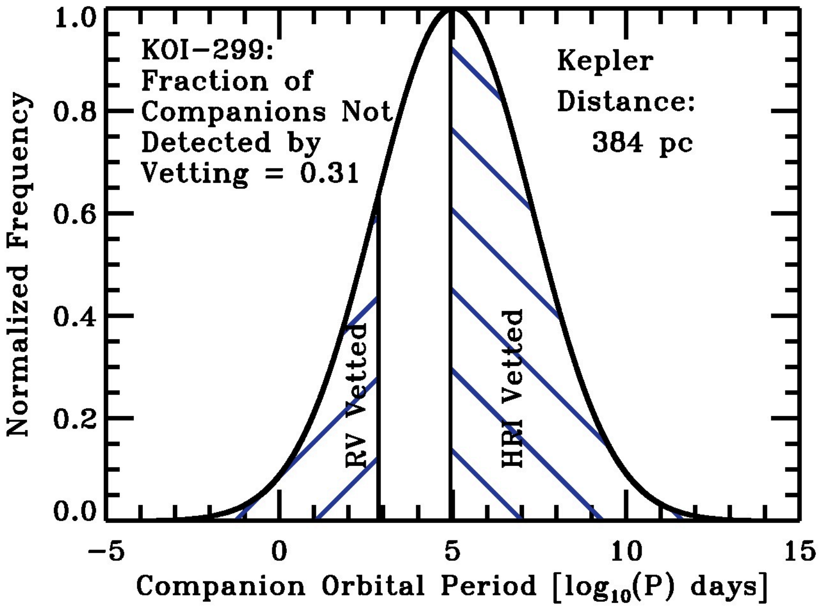
Kepler follow-up with speckle imaging

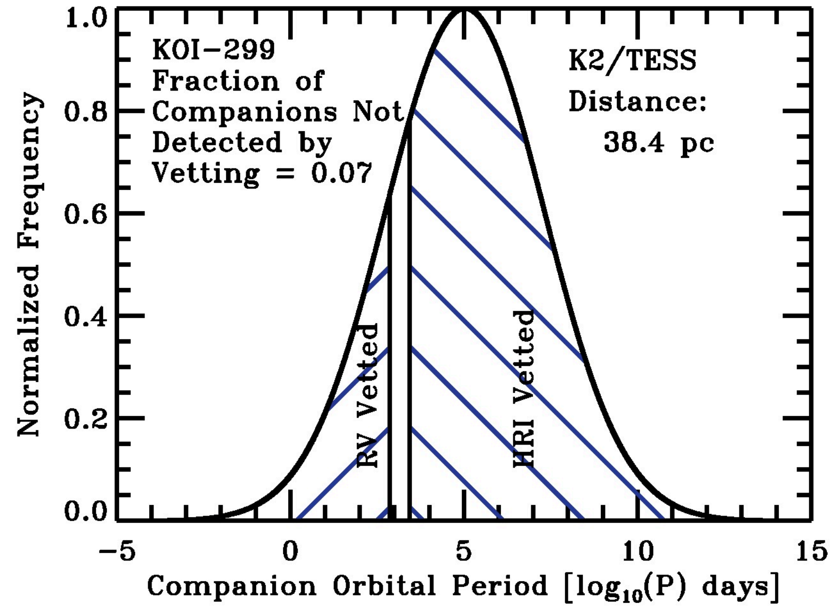


Furlan et al., 2016

DSSI: 40+ separate papers with over >200 (small) planet validations.
DSSI FOP data used in all Kepler, and K2 catalogue papers, >1000 Kepler & K2 KOIs and RV planet host star speckle images in NASA archive

Binary Star Detection – RV vs. high-resolution imaging

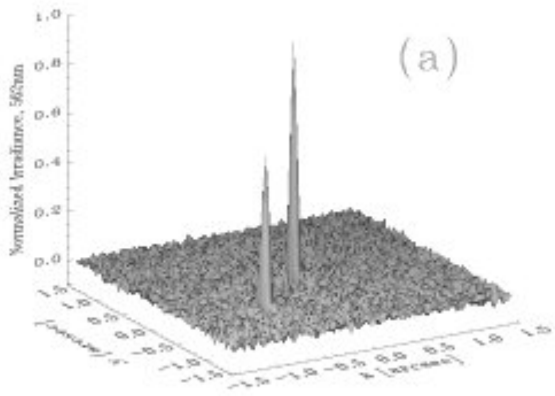




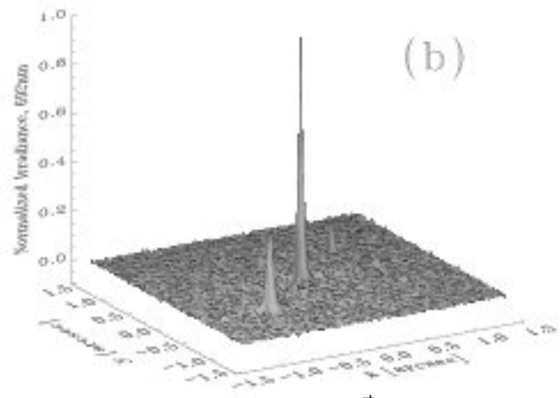
- Delta magnitudes of up to 5, ~0.04" – 1.4" spatial resolution
- 5-20 AU resolution for typical Kepler stars
- 1-2 AU resolution for K2 and TESS stars, nearby stars, and for typical RV planet host stars
- Need hi-res imaging in both hemispheres (DSSI also at Gemini-N and S)

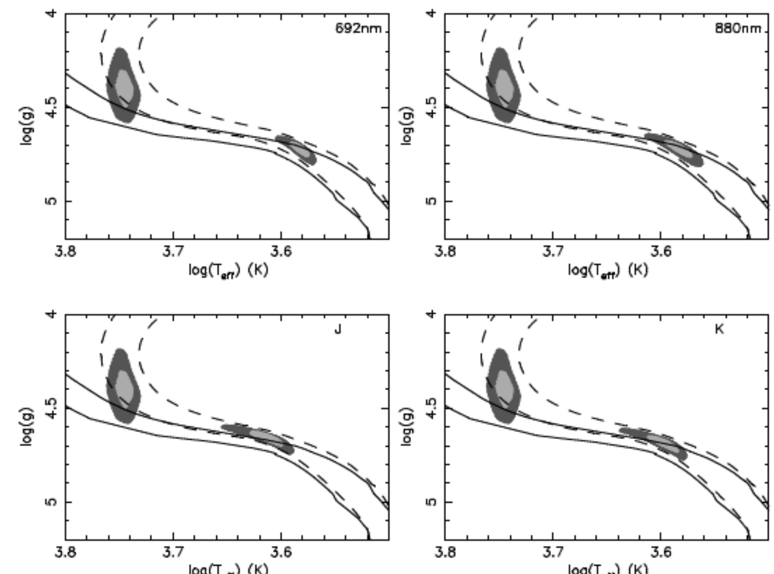
K2 Exoplanet candidate

562 nm

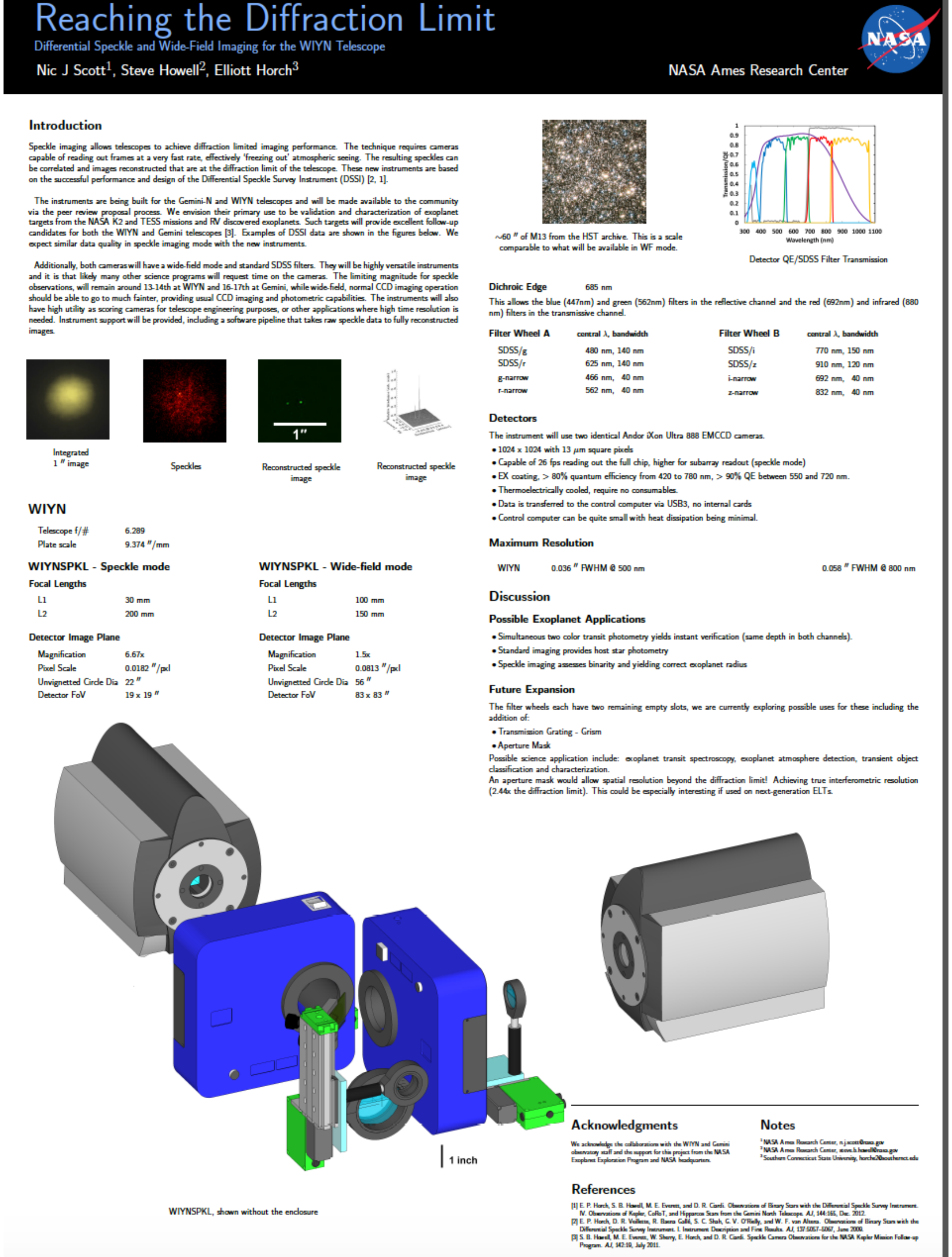


692 nm





Isochrone fits yields:
True companion?
M, L, R, M_v … for both stars
Correct planet radius
Which star planet orbits



Reaching the Diffraction Limit

Differential Speckle and Wide-Field Imaging for the WIYN Telescope

Nic J Scott[1], Steve Howell[2], Elliott Horch[3]

NASA Ames Research Center

Introduction

Speckle imaging allows telescopes to achieve diffraction limited imaging performance. The technique requires cameras capable of reading out frames at a very fast rate, effectively 'freezing out' atmospheric seeing. The resulting speckles can be correlated and images reconstructed that are at the diffraction limit of the telescope. These new instruments are based on the successful performance and design of the Differential Speckle Survey Instrument (DSSI) [2, 1].

The instruments are being built for the Gemini-N and WIYN telescopes and will be made available to the community via the peer review proposal process. We envision their primary use to be validation and characterization of exoplanet targets from the NASA K2 and TESS missions and RV discovered exoplanets. Such targets will provide excellent follow-up candidates for both the WIYN and Gemini telescopes [3]. Examples of DSSI data are shown in the figures below. We expect similar data quality in speckle imaging mode with the new instruments.

Additionally, both cameras will have a wide-field mode and standard SDSS filters. They will be highly versatile instruments and it is that likely many other science programs will request time on the cameras. The limiting magnitude for speckle observations, will remain around 13-14th at WIYN and 16-17th at Gemini, while wide-field, normal CCD imaging operation should be able to go to much fainter, providing usual CCD imaging and photometric capabilities. The instruments will also have high utility as scoring cameras for telescope engineering purposes, or other applications where high time resolution is needed. Instrument support will be provided, including a software pipeline that takes raw speckle data to fully reconstructed images.

Integrated 1 ″ image

Speckles

1″

Reconstructed speckle image

Reconstructed speckle image

WIYN

Telescope f/#	6.289
Plate scale	9.374 ″/mm

WIYNSPKL - Speckle mode

Focal Lengths

L1	30 mm
L2	200 mm

Detector Image Plane

Magnification	6.67x
Pixel Scale	0.0182 ″/pxl
Unvignetted Circle Dia	22 ″
Detector FoV	19 x 19 ″

WIYNSPKL - Wide-field mode

Focal Lengths

L1	100 mm
L2	150 mm

Detector Image Plane

Magnification	1.5x
Pixel Scale	0.0813 ″/pxl
Unvignetted Circle Dia	56 ″
Detector FoV	83 x 83 ″

1 inch

WIYNSPKL, shown without the enclosure

~60 ″ of M13 from the HST archive. This is a scale comparable to what will be available in WF mode.

Wavelength (nm)

Detector QE/SDSS Filter Transmission

Dichroic Edge 685 nm

This allows the blue (447nm) and green (562nm) filters in the reflective channel and the red (692nm) and infrared (880 nm) filters in the transmissive channel.

Filter Wheel A	central λ, bandwidth	Filter Wheel B	central λ, bandwidth
SDSS/g	480 nm, 140 nm	SDSS/i	770 nm, 150 nm
SDSS/r	625 nm, 140 nm	SDSS/z	910 nm, 120 nm
g-narrow	466 nm, 40 nm	i-narrow	692 nm, 40 nm
r-narrow	562 nm, 40 nm	z-narrow	832 nm, 40 nm

Detectors

The instrument will use two identical Andor iXon Ultra 888 EMCCD cameras.

- 1024 x 1024 with 13 μm square pixels
- Capable of 26 fps reading out the full chip, higher for subarray readout (speckle mode)
- EX coating, > 80% quantum efficiency from 420 to 780 nm, > 90% QE between 550 and 720 nm.
- Thermoelectrically cooled, require no consumables.
- Data is transferred to the control computer via USB3, no internal cards
- Control computer can be quite small with heat dissipation being minimal.

Maximum Resolution

WIYN 0.036 ″ FWHM @ 500 nm 0.058 ″ FWHM @ 800 nm

Discussion

Possible Exoplanet Applications

- Simultaneous two color transit photometry yields instant verification (same depth in both channels).
- Standard imaging provides host star photometry
- Speckle imaging assesses binarity and yielding correct exoplanet radius

Future Expansion

The filter wheels each have two remaining empty slots, we are currently exploring possible uses for these including the addition of:

- Transmission Grating - Grism
- Aperture Mask

Possible science application include: exoplanet transit spectroscopy, exoplanet atmosphere detection, transient object classification and characterization.

An aperture mask would allow spatial resolution beyond the diffraction limit! Achieving true interferometric resolution (2.44x the diffraction limit). This could be especially interesting if used on next-generation ELTs.

Acknowledgments

We acknowledge the collaborations with the WIYN and Gemini observatory staff and the support for this project from the NASA Exoplanet Exploration Program and NASA headquarters.

Notes

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[2] NASA Ames Research Center, steve.b.howell@nasa.gov
[3] Southern Connecticut State University, horche2@southernct.edu

References

[1] E. P. Horch, S. B. Howell, M. E. Everett, and D. R. Ciardi. Observations of Binary Stars with the Differential Speckle Survey Instrument. IV. Observations of Kepler, CoRoT, and Hipparcos Stars from the Gemini North Telescope. AJ, 144:165, Dec. 2012.
[2] E. P. Horch, D. R. Veillette, R. Baena Gallé, S. C. Shah, G. V. O'Rielly, and W. F. van Altena. Observations of Binary Stars with the Differential Speckle Survey Instrument. I. Instrument Description and First Results. AJ, 137:5057–5067, June 2009.
[3] S. B. Howell, M. E. Everett, W. Sherry, E. Horch, and D. R. Ciardi. Speckle Camera Observations for the NASA Kepler Mission Follow-up Program. AJ, 142:19, July 2011.

WIYNSPKL: New camera to be commissioned at WIYN in early Oct 2016

1024 X 1024 EMCCDs
Narrow and SDSS filters
Speckle ~20" mode
Wide-field ~60" mode
Fast readout, 26 fps

NN-EXPLORE "speckle" postdoc at NOAO to help community
(July 2016)